1965

A systems analysis formulation and criteria determination for ship maintenance policy optimization

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Monterey, California: U.S. Naval Postgraduate School

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by

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
OPERATIONS RESEARCH

United States Naval Postgraduate School
Monterey, California

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IN

OPERATIONS RESEARCH

from the

United States Naval Postgraduate School

ABSTRACT

The Navy has put much effort into development of computerized maintenance data collection, reduction, and storage systems but has not sufficiently developed methods for analysis and utilization of this information. To formulate the warship maintenance optimization problem a general background of the Navy's maintenance system is given and from this description annual operation and maintenance cost emerges as a valid criterion for judging alternative maintenance policies. A discussion of dependent and independent variables is included for use in derived models utilizing least squares regression techniques for estimation of annual operation and maintenance cost.

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1. Introduction.

The cost of maintaining naval ships has greatly increased in the years since World War II. The magnitude of this cost is demonstrable by the statement that "approximately twenty cents of every dollar the Navy spends for procurement, maintenance, and operation of warships (personnel pay excluded) is spent for procurement of material."[1] Prior to World War II the problems facing naval maintenance management personnel were relatively inexpensive, direct and uncomplicated. The Navy, recognizing that the problem has become more complicated and costly, has taken steps to provide maintenance managers with better information and decision bases by utilizing the burgeoning capabilities of electronic computer technology. Full benefits cannot be derived from this additional information for maintenance decisions however without the use of mathematical statistics, a science about which many naval officers have little knowledge and consequently distrust or ignore.

This thesis will formulate a criterion which may be used in selecting from among alternative maintenance policies. Since the correct solution to any problem depends to a great extent on a true understanding of what the problem really is and wherein the difficulties occur, the general nature of Navy ship maintenance will be discussed. From an understanding of the problem, the relevant costs, and alternatives annual operating and maintenance cost will be suggested as the proper cost to be used in selecting optimal maintenance policies. Relevant data elements and statistical methods with which annual operating and maintenance cost may be qualitatively determined and applied as a criterion will be formulated.

[1] J. E. Hamilton, Experience in Data Collection; Summary (Washington, D. C.: The George Washington University, Logistics Research Project, T-127/60, 1961), p. 5.

2. Background.

The principal aim of management of warship maintenance is to obtain a well defined level of ship material readiness with a minimum cost of resource inputs.[2] This criterion for judging the cost and effectiveness of maintenance policies is, with the present state of maintenance management, difficult, if not impossible, to use. The major problem in application of this criterion arises from the inability to qualitatively measure ship material readiness.

Ship material readiness may generally be considered to be a function of two factors, the first of which is condition, or state of repair, of the material and equipment that constitute the ship. The second is the availability of the ship's equipment, which we may define as the expected condition at a future time.[3] These factors are not predictable with any degree of accuracy for a modern warship as an entity but approximations to them, combined with general experience in the operation, maintenance, and repair of ships do provide a practicable intuitive basis for judging material readiness.[4]

Given the hypothesis that appropriate Navy commanders can measure a ship's material readiness we may attempt to optimize the maintenance policies which will achieve this happy state. "Optimum" here refers to

[2]The alternative approach of maximizing ship material readiness for a given maintenance budget is not considered because of the difficulties inherent in measuring material readiness.

[3]A third factor, environmental changes affecting a ship's operational readiness, is sometimes included. Reference [8] contains a thorough discussion of ship material readiness and ship operational readiness.

[4]Some proximate measures of a ship's material readiness are provided by results of Board of Inspection and Survey reports and Operational Readiness Inspections.

a minimum cost condition; in reality we would be satisfied to find more efficient maintenance policies, i.e., a lesser cost combination of resources than presently used.

A particular ship's life may be divided into four phases which have been called[5]

The planning phase

The construction phase

The outfitting and shakedown phase

The operating phase

The operating phase is generally considered to be the most important in maintenance cost analyses but the subject is important during the other three phases of a ship's life.

The operating phase of a ship's life is divided into a number of operating periods separated by regularly scheduled overhauls. These operating periods may be further subdivided by restricted availabilities and upkeep periods. This maintenance cycle which occurs during the operating phase of a ship's life is shown in Fig. 1 (upkeep periods are not included).

Regular overhauls are intended to overcome or reduce the effects of deterioration and obsolescence. The restricted availabilities are assigned for the accomplishment of specific jobs and upkeep periods are assigned to permit the ship's force to accomplish repair work with minimum interference but during all phases of the overhaul cycle the ship's force performs maintenance. This cycle may be interrupted for particular

[5] J. E. Hamilton, Experience in Data Collection; Summary (Washington, D. C.: The George Washington University, Logistics Research Project, T-127/60, 1961), pp. 35-51.

ships by interim shipyard overhauls, unscheduled yard or availability periods, or decommissioning and a regular overhaul may be combined with extensive modernization, as is done by the FRAM (Fleet Rehabilitation and Modernization) program.

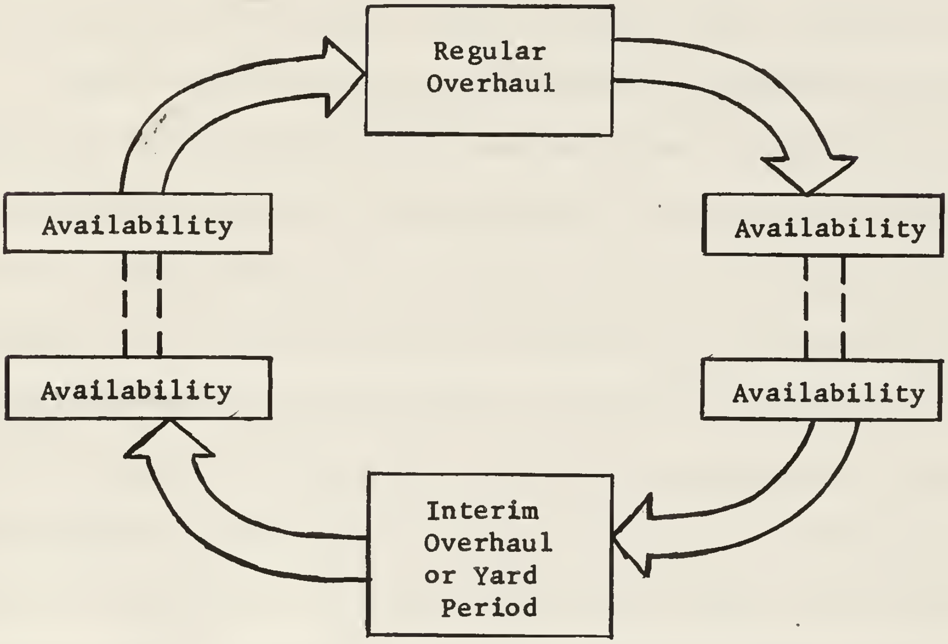

Figure 1. Ship's Overhaul Cycle

Maintenance during the overhaul cycle may be performed by the ship's own personnel, naval and commercial shipyards (including advanced repair bases) or afloat repair facilities (tenders and repair ships). The planning and control of these maintenance sources form the alternatives available for optimizing ship material readiness during the operating phase of the ship's life.

The problem selected for analysis is that of investigating factors which affect the cost of maintaining a warship during the operating phase

of its life. This sub-problem of the Navy's entire maintenance effort will not include investigation of efficient operation of shipyard and tender facilities except for the resources used by these repair facilities in direct maintenance of warships, e.g., establishing optimal overhaul cycle lengths. Bearing this in mind we may consider the cost attributable to maintenance inputs of labor, time, capital, and dollars.

Labor costs for maintenance performed by shipyards are easily defined and obtained [9] but problems arise when considering the value of naval personnel manhours. The real cost to the Navy of an hour of maintenance labor performed by a sailor is generally not the value of his wages, it is the value of his time utilized in its next best use. When considering tender personnel these alternative uses might be (1) maintenance labor on another ship, (2) filling another naval billet, e.g., as a member of a warship's crew, or (3) return to civilian life. No realistic value can be assigned to the alternative use of labor on another ship. The value of a warship crewman's labor is equally difficult to define for his alternative uses are either (1) not being assigned to the ship, or (2) the value of training sacrified for maintenance time. Since a specific constraint is placed on ship manpower levels by the need for manning battle stations, which on warships is generally not less than the need for maintenance personnel, we will not in this analysis consider the alternative of reducing (or increasing) ship personnel manning levels. The alternative cost of lost training time has no quantitative measure. These considerations place us in a quandary; naval manhours are an important maintenance resource yet we cannot place a realistic value on them.

In this analysis naval personnel manhours will be treated separately from other resource constraints and labor time estimating relationships will be developed in such a manner as to permit assignment of arbitrary values to them in applications where labor time is a relevant consideration.

Annual operating and maintenance cost includes ship's personnel cost, hence shipboard manhours will generally be important when making decisions about better alternative uses for this labor time. A value of tender personnel manhours could be derived by determining the entire crew's wages and allocating this to time utilized in repair of other vessels. Such a method might over-value tender manhours in peacetime and under-value them in wartime but at least this is one way in which to obtain an approximate cost.

Availability time is a period of time assigned to a ship by competent authority for the uninterrupted accomplishment of work which requires services of a repair activity ashore or afloat. When a ship is in availability status its services as a warship are lost; this constitutes a real cost. Most force structure analyses account for this opportunity cost by using the "pipeline" method, i.e., assuming that it takes several ships in the force to keep one on station. This formulation is not practicable for maintenance cost analysis however so it will be necessary to explicitly account for this opportunity cost and, in the interest of flexibility, account for it in such a way as to enable its elimination for use in cost effectiveness studies utilizing the "pipeline" method. A more complete discussion of this cost is contained in reference [5].

Several costs generally defined as capital expenditures will be considered. First among these is overhead costs for repair facilities afloat and ashore. Overhead cost is a factor in each repair action and is necessary for many budgetary considerations. This item is generally identifiable for shipyard maintenance [9] but no overhead will be charged to tenders, for two reasons. First, this factor probably has little significance in the sub-problem being considered, and secondly, it is believed there is no practical alternative to having tenders in peacetime forces because of their necessity in wartime. When studying tender maintenance itself this overhead cost would be an important consideration.

The last capital cost discussed is the cost incurred by the attenuation of the capital assets of an individual ship. This cost is typically estimated by dividing the ship's initial cost by its assumed lifetime [5]. Since this capital depletion does not require the expenditure of funds other than those required for maintenance purposes, this cost is not relevant for this analysis.

Economists argue that monetary, or dollar, constraints are not perfect indicators of resource utilization [10] but this analysis assumes that dollars are an adequate measure of maintenance and material costs. All maintenance resources will be transformed into dollar costs. In many cases we can use standard costs or values assigned by various bureaus, e.g., some spare parts costs assigned by BUSANDA; in other cases, as for opportunity cost of ship availability time, we must find an acceptably accurate method of defining these dollar values.[6]

[6]Standard costs are based on engineering estimates and time studies, then validated by analysis of accounting data. A discussion of standard versus other types of cost estimates is contained in [13].

To properly judge the effect of various maintenance policies on the amount of resources required to maintain a defined level of ship material readiness we must be able to measure and compare the resources required by these alternative policies. The criteria utilized to select optimal policies must properly account for these costs.

Ship maintenance costs may be divided into three general components; costs incurred by the ship's force in its repairs and maintenance to the ship, costs incurred during tender periods and shipyard availabilities between regular overhauls, and costs of regular overhauls [9]. We may not want to minimize any one of these costs individually; to do so could be an expensive sub-optimization since costs incurred by these three alternative maintenance resources are interdependent and in fact may be considered to be substitutes. It is futile, for example, to speculate on the effect a high overhaul cost would have on future tender availability costs. A ship in poor material condition may require high cost overhaul, tender and ship's force maintenance while another ship might show decreased tender and ship's force costs after receiving a thorough overhaul. This "feedback" relationship is not desirable in statistical analyses [4] but any measure of maintenance effectiveness must account for it in some way. These considerations also imply that a selected criterion must account for at least the entire overhaul cycle maintenance cost.

In this context the Navy can make one of two possible decisions when considering the programming of ship maintenance funds. The first is whether to retain the ship in service or decommission it. The second is whether to retain the ship in service and modernize or repair it.

The correct decision is dependent on both the predicted effectiveness of the ship and the future discounted cost streams for each alternative. The cost portion of this decision basis is dependent to a great extent on the ship's annual operating and maintenance cost for its entire economic lifetime [5].

All of the factors discussed thus far point to annual operation and maintenance cost as a proper criterion for judging the resources required by alternative maintenance policies. The remainder of this analysis will be concerned with deriving estimating relationships which may be used to determine that cost. Determination of the dependent variable, proposed independent variables and applicable regression models will be discussed. The relationships are not formulated for the purpose of predicting future maintenance costs for a particular ship. They will, however, form a basis on which predictions of annual operation and maintenance cost can be made for a number of ships with different maintenance histories and characteristics; such predictions would be valuable for use in military cost-effectiveness studies as well as in providing a measure of maintenance policy effectiveness.

3. Dependent Variable.

In order to derive an estimating relationship we must first define and collect data for determination of the dependent variable. This analysis is concerned with ships annual operating and maintenance cost oriented toward maintenance and material cost implications as opposed to total system force costs; hence the pertinent cost categories can be described by the designations of Table I. Of these nine costs those associated with regular overhauls, other non-regular repairs, maintenance material and some components of supplies and equipage are of particular interest. The remaining five categories can either be estimated individually [12] or existing estimates can be treated as input data.

Determination of the maintenance cost components will be considerably more difficult. Costs attributable to maintenance material and repairs performed by ship's force and during tender availabilities are obtainable as an output from the 3M System.[7] Shipyards do not, at present, report on the 3M System but data is available from shipyard departure reports for regular overhauls and from the appropriate Navy bureau or OPNAV office for the other shipyard repairs. A problem arises in determining annual supplies and equipage costs since the 3M System includes data on some equipage items.[8] There would be some duplication present in investment costs for replacing some items of equipage, e.g.,

[7]The Standard Navy Maintenance and Material Management System (3M System), discussed in Section 5 of this report, is an electronic maintenance data processing system presently in the final stages of development.

[8]"Supplies and equipage" is a budgetary term for a variety of shipboard supplies and materials including repair parts for some equipments; equipage items such as lifejackets, foul weather clothing, and damage control equipment; consumable supplies such as lubricants, paint and office supplies. Miscellaneous services are also included. Fuel, water and utilities are not included.

Cost Category	Component	Administering Bureau	OPNAV Sponsor
A. Ship Personnel			
(1) Pay, allowances, subsistence, etc.	C_k	BUPERS	OP-01
(2) Training	C_k	BUPERS	OP-01
(3) Medical care	C_k	BUMED	OP-01
B. Materials, Maintenance and Supplies			
(4) Fuel and utilities	C_k	BUSHIPS	OP-04
(5) Expendable ordnance	C_k	BUWEPS	
(6) Regular overhauls			
(7) Other, non-regular repairs	C_m	Various Cognizant Bureaus	OP-05
(8) Maintenance material	C_m		
(9) Supplies and equipage	C_m, C_k		

TABLE I

Cost Breakdown of Annual Operating and Maintenance Funds

some repair parts accounted for both by budgetary estimation of supplies and equipage and 3M System material costs and likely would be a small fraction of this cost category, hence any duplication might be ignored in preliminary analyses. If the analyst obtains a separate estimate of supplies cost this duplication could be completely eliminated.

Following the logic of this cost breakdown we can consider annual operation and maintenance cost to be composed of two components; the first component is those factors which can be assumed invariant with maintenance and material costs and the second component consists of those costs resulting directly from material and maintenance expenditures. Analytically

$$C = C_K + C_M$$

where the annual operating and maintenance cost, C, is the sum of C_K, maintenance independent costs, and C_M, the material and maintenance cost. Each of the nine cost categories of Table I has been specified as a component of either C_K or C_M; (the standard budgetary estimate of supplies and equipage can be subdivided into separate components) and the dependent variable C can be determined from their sum.

The assumption that some components of annual operation and maintenance cost, e.g., personnel and fuel costs, are not functions of maintenance parameters is not strictly true. Fuel cost, for example, would be low in a year including a yard overhaul. The dependent variable used in the models, however, will be C_M composed of the components defined in Table I. This assumption is a sub-optimization [16]. It is inevitable that the many facets of ship maintenance decision-making be broken down into component parts, "slicing off" a sub-problem in each case and

fixing or ignoring other relevant factors and the resulting analysis is intended to help find policies that are improvements over existing or proposed solutions, to major maintenance sub-problems. To use a homely aphorism, "Shoes don't fit perfectly very often, but a lot of ground can be covered just the same."

4. Independent Variables.

This section contains an investigation of characteristic variables which may be used to predict maintenance costs. It is felt that by judicious consideration of these variables prior to performing the analysis a great deal of effort in data collection and analysis time can be avoided. Many of the discussed variables are discrete, that is, a ship either possesses that characteristic or it does not. Other variables are inter-dependent, e.g., full and light load displacement, hence it may be adequate to include only one of these variables in the model.

It is not asserted that the explanatory variables listed below are causes of maintenance costs but rather that they may be useful in predicting these costs.

(1) - SHIP TYPE is a source of maintenance cost variation; annual operation and maintenance cost is greater for an aircraft carrier than for a minesweeper. A model could be developed which would by inclusion of the proper descriptive variables enable cost prediction for all ship types by one equation. It is probable, however, that one equation would be long and complicated and that some predictive accuracy would be sacrificed. A better method would be to aggregate ships into similar classes and develop a separate model for each class. The Navy's type designation is one class definition and will form the basis for our models. All destroyer types will be in one class, minesweepers in another. With proper selection of explanatory variables to differentiate between ships within these classes we may account for individual ship differences. A trade-off must be made between the number of classes considered and accuracy, for predictive accuracy may be highly sensitive to

the class definition. One analysis of yard overhaul costs [4] indicates that in some cases several ship types may be considered simultaneously in one model. In that analysis one cruiser was included with DD types, then DD types alone were considered; the inclusion of the cruiser did not distort the predictions. This single analysis, limited in scope, cannot be considered conclusive for our purposes, hence it is recommended that initial analyses aggregate ships into classes by Navy type designation.

(2) - The SIZE of a ship influences its maintenance cost. If the class breakdowns were very detailed (DD, DL, DLG, etc.) this variable might not be significant, but when considering larger classes (all DD types including DD, DL, DLG, etc.) ship size is likely to be an important variable. There are several variables that could be used to describe a ship's size, some of which are full load or light load displacement, length, draft and beam. Within a given ship type, however, these factors are generally related, hence it should be sufficient to include only one of these parameters in our model. Analyses of warship construction costs [11] and overhaul costs [4] have both shown high correlation of costs with full load displacement so there exists some justification for including this variable for explanation of ship size with this ship class definition. It should not be necessary to include more size variables than length and full load displacement.

(3) - The method of PROPULSION is another source of cost variation. For some classes this presents no difficulty; carriers for example are all powered by steam turbine reduction systems. Ships in other classes may have different power plants; destroyer types, for example, may have

geared steam turbines, turbo-electric, or diesel propulsion plants. Ship classes which pose this problem can generally be subdivided into two classes (most DD types are either steam powered or diesel driven) hence inclusion of a discrete variable may be adequate. For destroyer types the discrete variable could be "zero" for steam driven ships and "one" for other propulsion methods, thus considering diesel and other propulsion systems similar for cost analysis purposes.

(4) - FUEL type is not a major problem if propulsion method is in the model. Nuclear power could be accounted for by a discrete variable and the cost effects of other types of fuel sources would be included in the effects of propulsion type explanatory variables.

(5) - The SUSTAINED SPEED and SHAFT HORSEPOWER (SHP) of a ship could be significant independent variables. There is a wide range in speed capabilities and SHP for various destroyer types that is significant in estimating ship construction cost [11] but this difference may be less significant for maintenance cost analysis, especially if propulsion method and size are two of the independent variables in the model. An analysis of ship overhaul costs [4] indicates a correlation between overhaul costs and SHP and recommends the use of a "power density" variable, such as horsepower per ton of displacement in future analyses.

(6) - The ARMAMENT of ships within classes may vary considerably. The primary difference is the presence of guided missiles on some combatant ships. This could be taken into account by a discrete variable.

(7) - The CLASS SIZE may be a factor in maintenance cost variation. In ship construction cost the lead ship (first of its type) cost is significantly greater than follow-on ship construction costs [11], however

it is likely this would not have much effect on maintenance cost after a lead ship's initial overhauls. The number of ships in the class might be significant however. A large number of ships in a class might have a "learning" effect on maintenance costs though this does not appear to be significant for ship construction costs [11]. This possible difference in "learning" significance for the two cost categories might result from the many construction yards as opposed to the few tender and naval shipyard overhaul facilities and their similarities. Data for this variable is easily obtainable and since its effect is unknown the number of ships in the class should be included in the model.

(8) - The SEVERITY of a ship's operating schedule would be expected to have an effect on its maintenance costs. There is evidence, for example, that the number of times electronic equipment is turned on or off is an important parameter in its failure rate. A model such as the one being investigated cannot consider effects such as these in detail but rather must account for them by use of variables which are more general and for which data is easily obtainable. Independent variables which might represent severity of ship's use are fuel consumption, miles steamed (as measured by engine miles) or percent of time at sea; an arbitrary classification of severe and normal operation schedules might be used with discrete variables or a combination of one of the former might be used in conjunction with the discrete variable. Fuel consumption, unlike engine miles, picks up in-port steaming and may be preferable to engine miles. Fuel consumption is also an accelerated function of speed while engine miles are a linear function [4]; this acceleration property may be desirable in that equipment deterioration might be expected to

accelerate as the tempo of ship operations increases. Percent of time at sea might be a desirable variable to include in the model but would require much more effort in data collection and aggregation than would fuel consumption.

If discrete variables representing severity of operations were included it would be necessary to investigate each ship's operation schedule, then place this ship in one category or another; this would be a time-consuming and somewhat arbitrary process. Considering all these factors it is felt that fuel consumption would be the best explanatory variable to use to account for the tempo of a ship's operation schedule.

(9) - CASUALTY REPORTS are submitted by a ship when a material failure occurs which significantly reduces the capability of a ship to perform its assigned mission. It may be expected that maintenance costs will increase as the number of casualty reports filed by a ship increases but two related factors could change this effect. First, a casualty report may be filed only because of the lack of availability of an inexpensive, easy-to-install spare part. Secondly there is no clear-cut definition of "significant reduction in capability" hence the decision about submission of a casualty report is often subjective. For these reasons, and because it is impossible to predict submission of casualty reports, it is recommended that they not be included as independent variables. Some justification for this exists since they were found to be insignificant in an analysis of overhaul costs [4].

(10) - The AGE of a ship would be a possible source of maintenance cost variation. There are two ships ages which might be of interest. The first is the age of the ship since its initial construction.

Reference [3] might indicate that overhaul cost is invariant with ship's age but an analysis of overhaul costs as a function of age alone [4] showed that overhaul cost increased to a maximum at about 15 or 16 years of age, then decreased. This result, if false, might come from the lack of sufficient explanatory variables, wrong model form or structure, or the existing maintenance policies and budget decisions. If true this decreasing overhaul cost could have a significant effect on ship's force and availability maintenance costs.

The Navy is vitally concerned with the cost effects of modernization of old warships, hence the age of a ship since modernization is the second age variable that might be of considerable significance.[9]

(11) - The SHIPYARD in which a ship is initially built is a source of construction cost variation [11] and may be expected to have an effect on overhaul costs. It is not within the scope of this analysis to consider in detail the effect of different geographical locations of shipyards but it would be possible to investigate the effect on maintenance cost by overhauls conducted in naval as opposed to commercial shipyards. This could easily be done by use of discrete variables.

(12) - MAINTENANCE HISTORY should have a significant effect on maintenance and material costs. We could attempt to consider a ship's history reaching back as far as its initial construction but this would be difficult to do and is likely to have only a slight effect on present costs if other related variables, such as ship's age, are included in the analysis. A list of independent variables which might be significant

[9]Reference [4] indicates the Navy may have retarded the age effects of destroyers by five years in the FRAM program. Validation of this assertion would be useful for future maintenance decisions.

for this analysis is:

a. Last regular overhaul expenditures

b. Number of tender availabilities during the overhaul cycle

c. Number of shipyard availabilities during the overhaul cycle

d. Interim overhaul between regular overhauls; discrete variable or expenditures

e. Length of overhaul cycle

f. Ships force dollar expenditures on material and maintenance during overhaul cycle

g. Ships force maintenance manhours during overhaul cycle

h. Date of last regular overhaul

This list of recommended variables seems long but the primary purpose of this analysis is to investigate maintenance costs, hence maintenance history should play an important role. The list could even be extended to include expenditures incurred during restricted and technical availabilities. Other analysts might want to include other variables but within the scope of this analysis those recommended would be representative of a ship's maintenance history and might eliminate the need for some interdependent factors, such as average rate of occurrence of tender availabilities.

(13) - The passage of TIME may cause variation in maintenance costs resulting in part from the influences of inflationary price changes, productivity increases due to increased technological knowledge, and changing budgetary situations. This variable can be considered to account for miscellaneous influences which occur over time. If the variables listed previously under Maintenance History are used a time factor is present, hence another time variable need not be included in the model.

(14) - The ship's FUNCTION may have an effect on maintenance cost. For example, different levels of weapon and sensor system complexity have been found to be significant in overhaul cost estimation [4]. We may define a number of discrete variables to represent this functional complexity, e.g., designation for ASW or Radar roles for destroyer type ships. A separate variable has been included above for guided missile capability since those systems may be present on many ship types. If our analysis indicates a consistent ship type bias in the model, for example if we find that DLG costs are generally estimated low, then we could include a discrete variable for that type ship in our model under this functional variable category. The variables used in an analysis for this cost effect would be a function of the ships investigated and data available.

It is realized that other analysts might want to modify this list of independent variables but it is the author's judgment that those defined above represent the factors which are most likely to prove significant and for which data is most readily available for maintenance cost analyses.

5. Data Sources.

Collection and aggregation of warship maintenance data is a confusing and baffling process that confronts any analyst studying this problem. A large number of data sources are available (some more available than others) varying in content and completeness. This section will discuss those sources which either have been used in previous analyses or are deemed sufficiently complete and available to authorized users that they will prove to be valuable aids in maintenance data collection for the proposed analyses. The sources discussed do not exhaust the data collection alternatives and in some cases several recommendations are made.

The 3M System will be an important data source. It is a new system of maintenance and material management being introduced into the fleet this year, sponsored and directed by the Chief of Naval Operations. It is entitled "The Standard Navy Maintenance and Material Management System" and is known by the short title, "3M System." Basically the 3M System provides for the collection, processing, and compilation (by electronic accounting machines) of (1) manhour data, (2) maintenance data, and (3) ship (and aircraft) statistical data. The raw data is generated at the most basic source, i.e., from the technician who performs the maintenance task. Through the use of codes which can be extracted, key punched, and machine processed the mechanic records which equipment he worked on (which system, sub-system or component), how the failure occurred, when it was discovered, what corrective action was taken to effect the repair, what parts were used in repair, how long the job took in manhours, and what ship's department did the work. Dollar costs of repair parts will be correlated with this data at the data storage facility.

The data storage facility is located at The George Washington University Naval Logistics Research Project in Washington, D. C. during 3M System development but will soon be shifted to direct Navy control at the Fleet Material Support Office, Mechanicsburg, Pennsylvania. This system will provide one central fund of maintenance data for naval ships (and tenders) and hopefully at a later date, shipyards, which can be drawn upon by authorized users eliminating the duplication now found in our manual reporting systems.

The most convenient source of shipyard cost data is the yard departure reports found in BUSHIPS. A thorough analysis and explanation of data aggregation from departure reports may be found in reference [7]. Dates on which any ship has been in an availability status may be obtained from the Overhaul and Availability File, OPNAV (OP-43). Information on ship's characteristics may be obtained from reference [9] although if data is desired about which specific systems are installed in a ship it will be necessary to refer to OPNAV (OP-43), BUSHIPS or the individual ship's home overhaul shipyard. Data on ship operation schedules and some tender availability information is available from the appropriate ship Type Commander.

6. Models.

This section discusses several models which may be used to describe ship's annual operating and maintenance cost. Cost components, dependent and independent variables have been discussed; we will now investigate the traits desired in our model and suggest various ways to obtain these qualities with the belief that careful consideration, prior to actual analysis, of the model's structural and functional form will save much time and effort in the analysis. There are a number of pitfalls in the path of model construction which may lead to two types of errors, simple mistakes or fallacies [8]. It will be the analyst's function to avoid mistakes but fallacies are caused by errors in logic and we must eliminate these from our model. This must be done by careful consideration of the model's structural form and the variables that compose it since there is a notable lack of prior analysis to serve as a guide. Even with this prior consideration the analyst must be prepared to use various combinations of independent variables in the proposed models, for the decision as to which model should be used depends on these variables, as well as on the model's structural and functional form.

We have considered annual operation and maintenance cost to be the sum of two costs,

$$C = C_K + C_M$$

where C_K, the operational costs invariant with respect to maintenance costs, can be determined by methods discussed in the Dependent Variable Section. C_M, the annual material and maintenance cost, is the component which must be determined.

Two statistical approaches to the estimation of C_M are possible [3].

The first method is utilization of complete historical data for a ship sample relatively small in size compared to the second method, which is to analyze a larger sample of ships during some recent and relatively short time period. The restrictions on sample size and time interval considered are imposed by the practical limitations of computer size and data collection requirements. The historical series aggregation has many inherent difficulties chief among which are problems associated with time considerations, e.g., inflation and environmental changes. It is likely that a time variable will be present in any model selected but we do not desire a strong dependence on this variable; our model is to be dependent primarily on ship characteristics (including age) and maintenance variables, not time. There are other practical difficulties in data collection caused by budgetary policies which result in allocation of funds in such a way that in many cases a complete historical record of expenditures for a particular ship does not exist. Because of these difficulties it is recommended that the sample selected be large in size and that data be collected for at least one complete overhaul cycle for each ship in the sample. Prior to the existence of the 3M System this would have presented a difficult problem in data collection but is now a feasible approach.

A model of ships operation and maintenance costs may define ships by using descriptive variables such as length and age or it may consider a ship to be an aggregation of systems. The latter approach is intuitively appealing since ships consist of hulls containing a collection of subsystems each of which has a different economic lifetime and different maintenance characteristics.

The models proposed below do not specify which of the independent variables of Section 4 should be used but the model structure is designed for a combination of descriptive and discrete independent variables.

Model #1

The first model that will be considered predicts the overhaul cycle cost as a linear function of the independent variables. Analytically

$$C_c = a + \sum_{i=1}^{n} b_i X_i + U$$

where C_c is the overhaul cycle maintenance and material cost; $X_1, X_2, \ldots X_n$, are the independent variables and $a, b_1, b_2, \ldots b_n$ are the regression parameters. U is referred to as an error term [13] whose presence can be considered to account for the net effect of excluded variables and unpredictable randomness in maintenance costs which can be characterized only by inclusion of a random variable term. For purposes of practical statistics the distinction between these two reasons does not matter since we do not contend that we have included all relevant factors in the relationship and also because randomness, if present, merely adds to the variance. It is outside the scope of this paper to further describe the properties of least squares techniques since they may be found in any standard statistics textbook.

The prediction of overhaul cycle maintenance cost would be valuable for maintenance management but in many cases annual maintenance cost would be more useful. We could find an average cost by dividing C_c by the average overhaul cycle length, $\bar{t}$, in years, for the sample ships. This method might not be a good estimator of annual material and

maintenance cost, however, since we are dividing the estimated cyclic cost by an average cycle length and any correlation between them could affect the dispersion of the estimates about the true mean. The second model will eliminate this problem.

Model #2

The dependent variable in the second model will be annual material and maintenance cost, C_M. For each ship in the sample we determine the cyclic material and maintenance cost, C_c, and divide by the overhaul cycle length, t, for the same ship. Hence

$$C_M = \frac{C_c}{t}$$

We now can find the regression curve of C on the independent variables $X_1, X_2, \ldots, X_n$. Analytically

$$C_M = \frac{C_c}{t} = a' + \sum_{i=1}^{n} b_i' X_i + U$$

where $a', b_1', b_2', \ldots, b_n'$ are the regression parameters and U is the error term. This method allows direct estimation of annual material and maintenance cost. One deficiency of this model is its inability to identify the magnitude of costs incurred by ship's force, availability or regular overhaul maintenance.

Model #3

The third model will consider costs to be incurred in one of three ways; ship's force maintenance, regular overhauls or availability maintenance between regular overhauls. We define the dependent variable to be the cyclic maintenance and material cost, C_c, and consider it to be composed of three components, (1) the cost of material and maintenance performed by the ship's force, S, (2) the cost of materials and maintenance

performed by repair facilities external to the ship between regular overhauls, T, and (3) the regular overhaul cost, Y. That is

$$C_c = S + T + Y$$

Each of the variables S, T, and Y are functions of the same set of independent variables and are determined by separate regression analyses. That is

$$S = d_o + \sum_{i=1}^{n} d_i X_i + U$$

$$T = d_o' + \sum_{i=1}^{n} d_i' X_i + U'$$

$$Y = d_o'' + \sum_{i=1}^{n} d_i'' X_i + U''$$

where d_i, d_i' and d_i'', $i = 1,2,\ldots,n$ are the regression parameters. U, U' and U" are error terms.

Model #4

Model number four may have the structure of any of the three preceding models but the philosophy for selecting independent variables will be different; it will look at ships as collections of systems fitted into hulls. We will have a large number of discrete variables to represent specific systems, e.g., SPS-21, SPS-35, SPS-41 radar systems; 5"/54, 5"/38, 3"/70 guns; or 600 and 1200 psi boiler and auxiliary systems. Each of these systems would be represented by a discrete random variable of value one if that system were installed or zero if it were not installed in a particular ship. Such a formulation would be useful for maintenance planning but is not practical for Navy warships since for any given class of ships there is a large number of possible systems, e.g.,

on a group of five destroyers there may be seven different radar systems. This discrete variable definition of systems would be practicable only if the number of systems represented were small. Since all possible ship's systems cannot be represented we must eliminate some from consideration and include some descriptive variables, such as length or full load displacement, in the model. We will now discuss a method for selection of the ship's systems to be represented by discrete variables.

It is quite likely that a large fraction of a particular ship's material and maintenance costs is generated by a small number of that ship's systems. Utilizing 3M System data we can determine the ship's force and tender maintenance costs for all systems on any ship. Unfortunately shipyards do not presently submit data to the 3M System and with existing overhaul records it is difficult to assign costs to a specific ship's system. This problem necessitates definition of high cost systems on the basis of ship's force and tender cost data only. This method could eliminate some important systems from consideration but with judicious use of intuition it is felt this difficulty could be overcome.

Having determined all of the high cost systems present on all ships within a given class, eliminating other systems from consideration, we may be able to further reduce the number of discrete variables needed to represent these ships by combining systems which are similar in function and have similar maintenance cost characteristics. This could distort the model's predictions for several reasons. First, there may be several such systems installed on a particular ship and second, we have little shipyard cost information on which to base our similar systems

classification. This method of classification should not be used unless the number of high cost systems in the class is too large for available computer routines. There is another way to maneuver around this difficulty however; we could eliminate some systems, e.g., boiler and auxiliary systems, from our discrete variable definition and include a smaller number of descriptive variables, e.g. SHP, in the model. This method would reduce the uniqueness of the model but might be the best method to use if we have too many independent variables.

Model Number	Type of Variables	Estimates
1	Descriptive	Overhaul cycle cost
2	Descriptive	Annual cost
3	Descriptive	Overhaul cycle costs for ships, availabilities, yards
4	Discrete	Overhaul cycle or annual cost

Table II

Comparison of Models

Table II lists the four proposed models and briefly describes their characteristics. Any one of them might prove valuable for a given purpose but certainly all should be investigated for predictive accuracy.

There are real costs not directly measurable in dollars that are important in formulation of maintenance policy. One of these real costs is maintenance manhours of naval personnel. It would be easy to determine average values of manhour expenditure by ship's force and tender personnel from 3M System data and it is felt this method would be

adequate for most purposes. If more information is desired about the factors which affect maintenance manhours, regression analysis using the models proposed for maintenance cost could be performed.

Time spent in availability status is, another component of real cost that is of interest. Reference [3] 4? investigated ships availability time (non-conversion or overhaul time) as a linear function of age. That is

$$t(i) = a + b\,i$$

where t(i) is the days of availability as a function of ship's age, i; a and b are regression parameters. The regression analysis suggested that for certain ship types t(i) was a constant, a, independent of ship age. This result can be explained intuitively but it is possible that other factors excluded by the homogeneity of the sample analyzed are important. For this reason more analysis of availability time as a function of other variables, e.g., operation schedules and descriptive variables, is necessary.

7. Testing the Models.

A great number of requirements and criteria for estimation efficiency may be applied to the models by various statistical tests but one factor in which we are particularly interested is statistically untestable [4], i.e., the feedback that exists between overhaul, availability, and ship's force expenditures. The effect this feedback will have on the predictive efficiency of any of the four proposed models is not known. It is likely that the effects of this interdependence would be minimized by the third model however.

Goodness-of-fit tests on the data from which the model was developed give important but nevertheless insufficient indications about the model's quality. The only method we have to ensure that our model will satisfy our estimation requirements is to test it with new data. The only hardship imposed by testing the model with new observations is in the collection of extra data. The results of such testing with observations outside the derived model's data base will determine if the model can survive and be accepted.

8. Conclusion.

The methodology recommended in this thesis can easily be utilized, with the aid of computers and some work in data collection, to obtain a valid measure of maintenance effectiveness. There are many problems to which this can be applied. Bureau and Type Commanders would like to know the answers to questions such as:

* Would it be advantageous to lengthen ship overhaul cycles?
* Can ships be assigned fewer tender availabilities?
* What is the true annual maintenance cost of a ship and how is it allocated?
* How large a maintenance budget should be requested next year?
* What particular ships cost more to maintain than others in their class, and why?

Answers to these questions depend on both cost and effectiveness, as discussed in this paper, and the methods presented will provide a quantitative basis on which to base the decisions required.

It is not asserted that solutions to all maintenance problems must be explicitly measured by this criterion. There are large classes of problems which can be solved with only rudimentary qualitative analysis and other classes of decisions which may be made on the basis of other types of statistical analyses, such as reliability theory and analysis of variance. Here a detailed method has been proposed for developing a criterion to be applied to high level maintenance policies during the operational phase of a ship's life. Only one important sub-problem of the Navy's maintenance program has been investigated. Not only must this analysis be performed but all the other facets of ship maintenance as yet untouched must be statistically analyzed before the Navy can

claim that it has optimized its maintenance policies. It is unlikely that this optimal situation will ever exist but considering the magnitude of the nation's resources being expended more efficient maintenance resource allocations should and can be made.

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